Electromagnetic Formation Flight (EMFF) and Applications to TPF

TPF Expo

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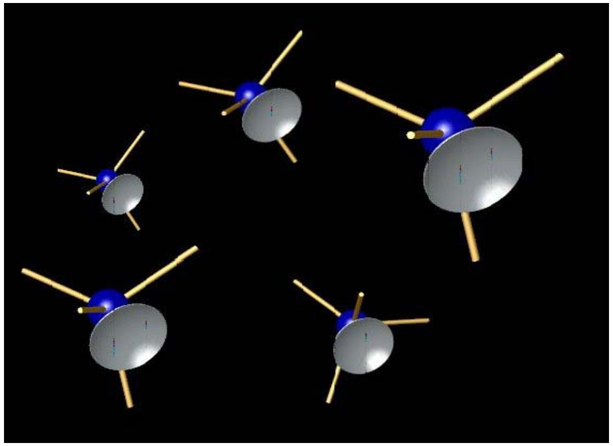
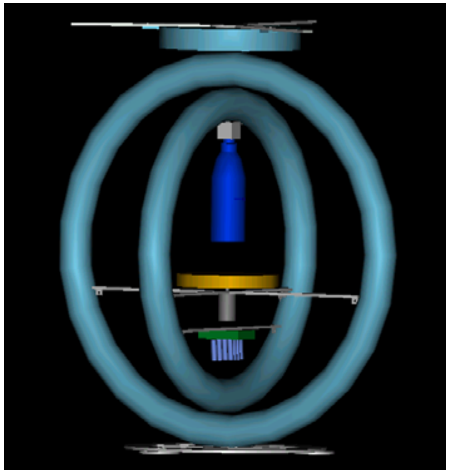




Outline

- Motivation
- Fundamental Principles
- Mission Applicability
- MIT EMFFORCE Testbed
- Conclusions

Motivation for EMFF

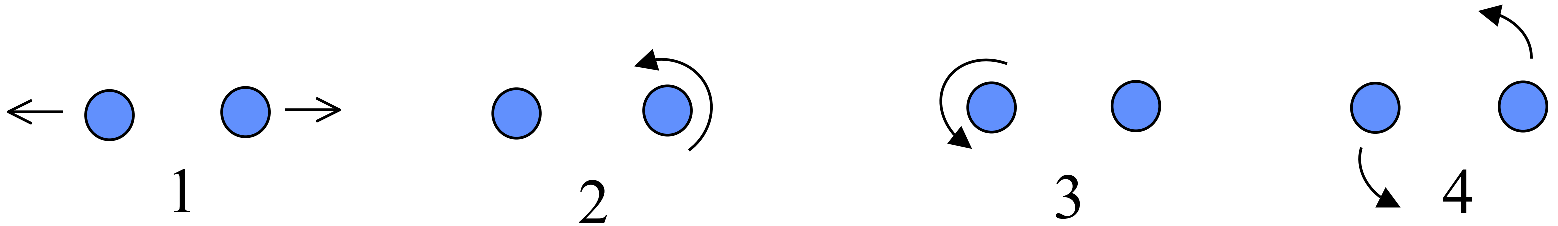
- **Traditional propulsion uses propellant as a reaction mass**
- **Advantages**
  - Ability to move center of mass of spacecraft
    (Momentum conserved when propellant is included)
  - Independent (and complete) control of each spacecraft
- **Disadvantages**
  - Propellant is a limited resource
  - Momentum conservation requires that the necessary propellant mass increase exponentially with the velocity increment (ΔV)
  - Propellant can be a contaminant to precision optics
- **Is there a technique that does not consume propellant?**
  - **Electromagnetic Formation Flight (EMFF)**

A Candidate Solution

- Yes, inter-spacecraft forces can be used!

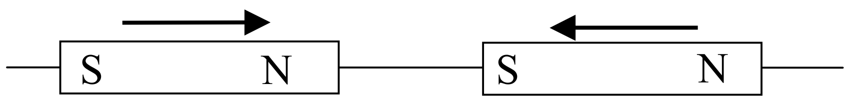
  … provided it is not necessary to alter the center of mass of the system.

- What forces must be transmitted between satellites to allow for all relative degrees of freedom to be controlled?
  - In 2-D, N spacecraft have $3N$ DOF, but we are only interested in controlling (and able to control) $3N$-2 (no translation of the center of mass)
  - For 2 spacecraft, that's 4 DOF:

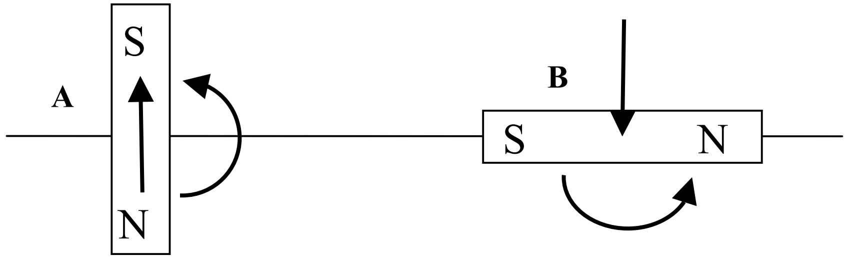


- (1)-(3) can be controlled using inter-spacecraft axial forces
- (2)-(3) can be controlled using reaction wheel torques
- (4) requires inter-spacecraft transverse forces, which can be created using electromagnetic dipoles

EMFF Concept

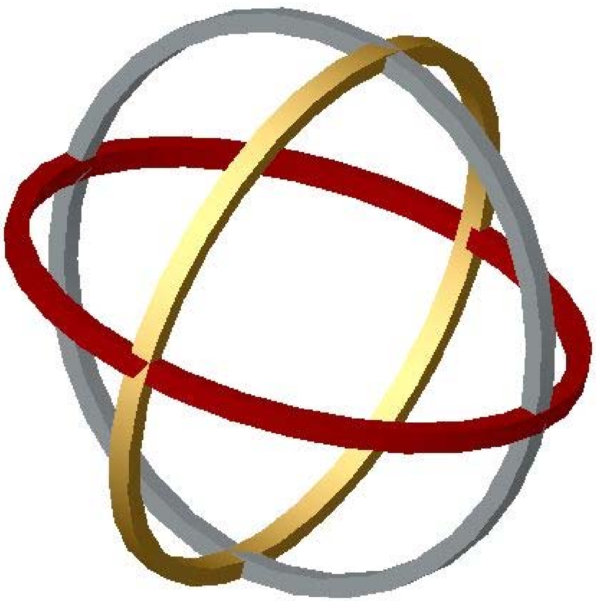


Axial forces maintain steady array rotation



Transverse forces initiate array spin-up

- Each vehicle has 3 orthogonal electromagnetic coils.
- In the far field, dipoles add as vectors.
  - 3 vector "components" on each vehicle form one "steerable" magnetic dipole
  - Electronic steering decouples the coils from the spacecraft rotational dynamics
- A reaction wheel assembly with 3 orthogonal wheels provides counter torques to maintain attitude



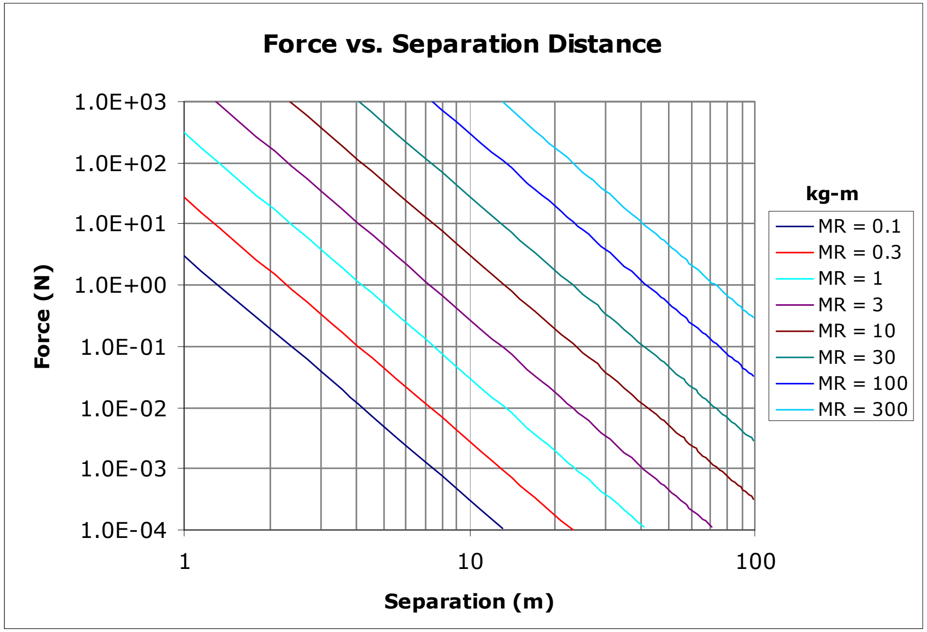
How Far Apart Will They Work?

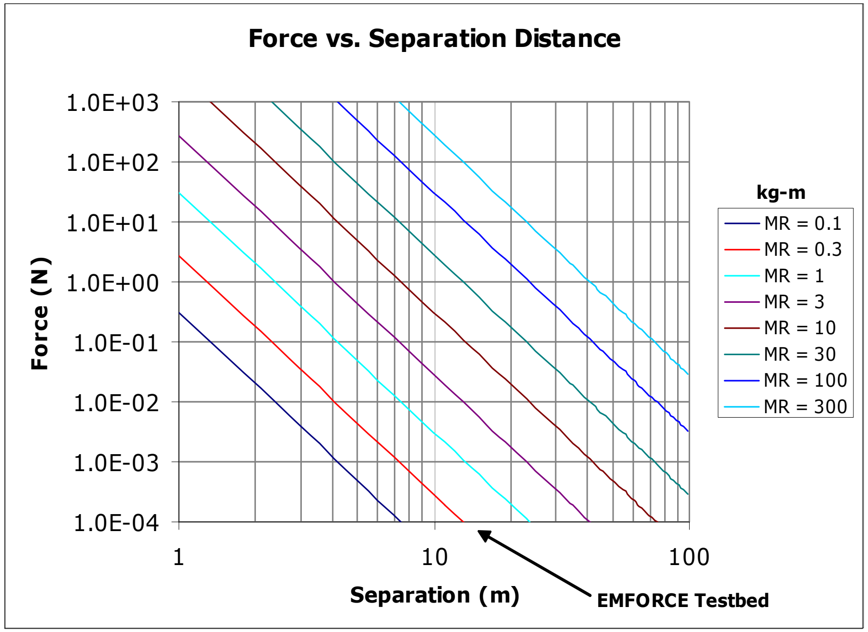
Axial force generated by a set of coils:

$$F \sim 31.2\ (M_C R_C)^2 \frac{1}{s^4}$$

The graph to the right shows a family of curves for various products of M_C and R_C

$$\frac{3}{2}(10^{-7})\left(\frac{I_C}{\rho}\right)^2 = 312\ \frac{\mathrm{m}^3}{\mathrm{kg\text{-}s}^2}$$





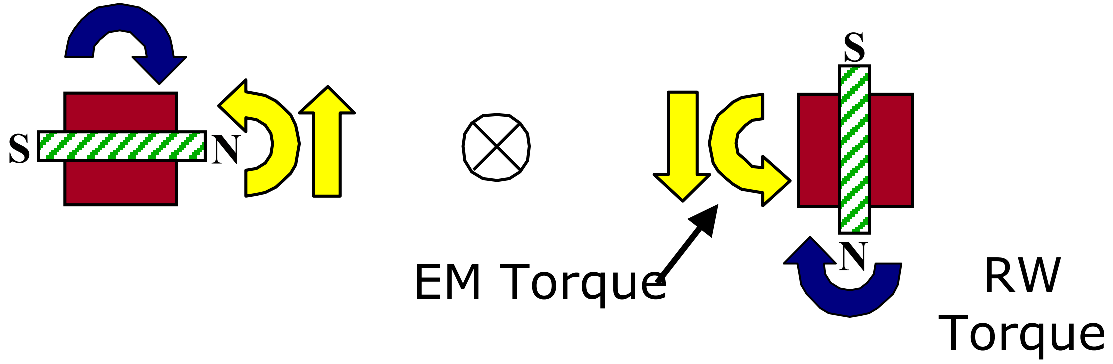
$$\frac{3}{2}(10^{-7})\left(\frac{I_C}{\rho}\right)^2 = 31.2\ \frac{\mathrm{m}^3}{\mathrm{kg\text{-}s}^2}$$

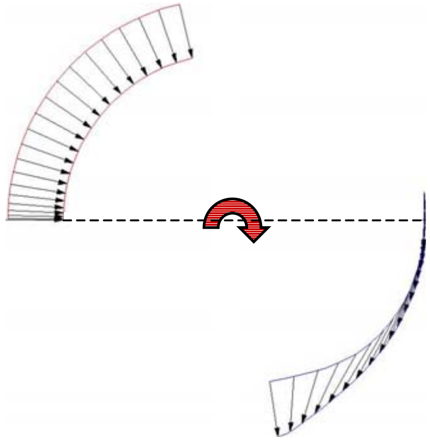
Example:

- 300 kg satellite, 2 m across, needs 10 mN of thrust, want M_C < 30 kg
- EMFF effective up to 40 meters
- 6MA/cm^2 extends to 560 meters

Satellite Formation Spin-Up

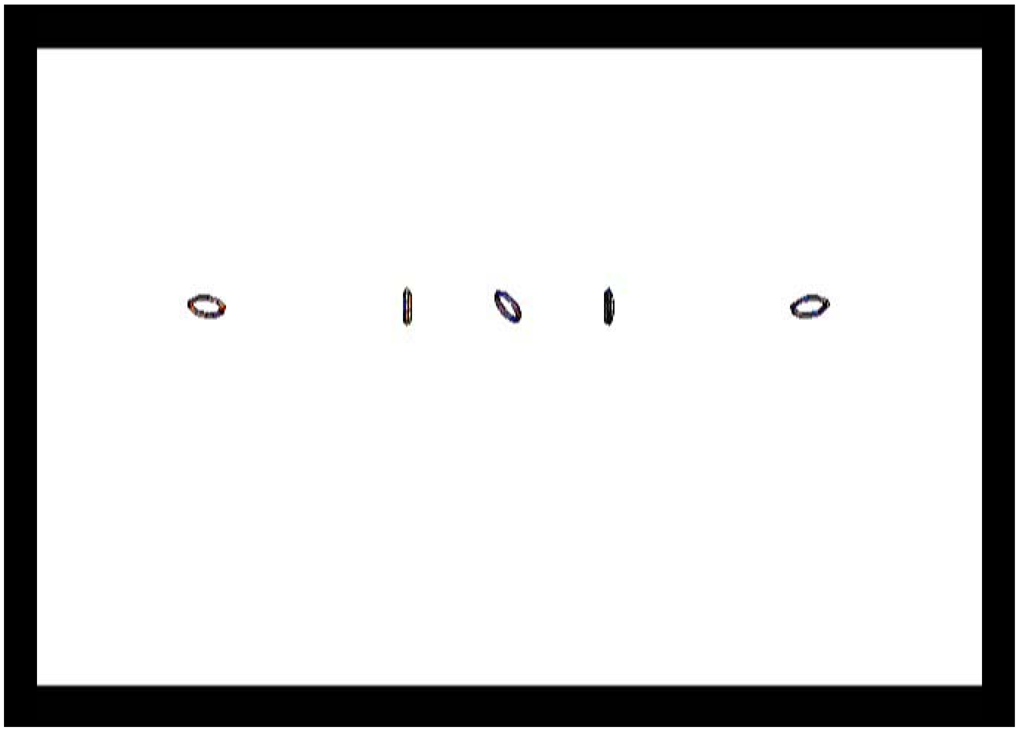
- Spin-up/spin-down
  - Spin-up to rotating array
  - Spin-down to reoriented baseline
- Electromagnets (EMs) exert forces/torques on each other
  - Equal and opposite "shearing" forces
  - Torques in the same direction
- Reaction wheels (RWs) are used to counteract EM torques
  - Initial torque caused by perpendicular-dipole orientation
  - RWs counter-torque to command EM orientation
  - Angular momentum conserved by shearing of the system



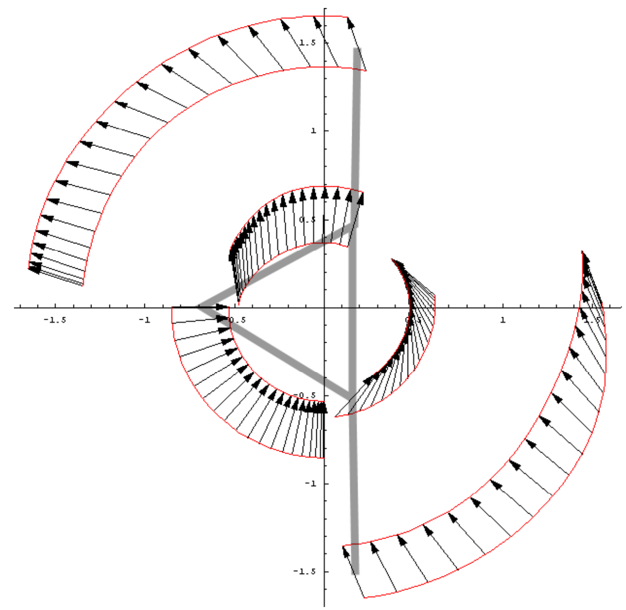


Satellite Formation Spin-Up

- Spin-up of complex formations can also be achieved using magnetic dipoles.
- Formations are not restricted to linear arrays!

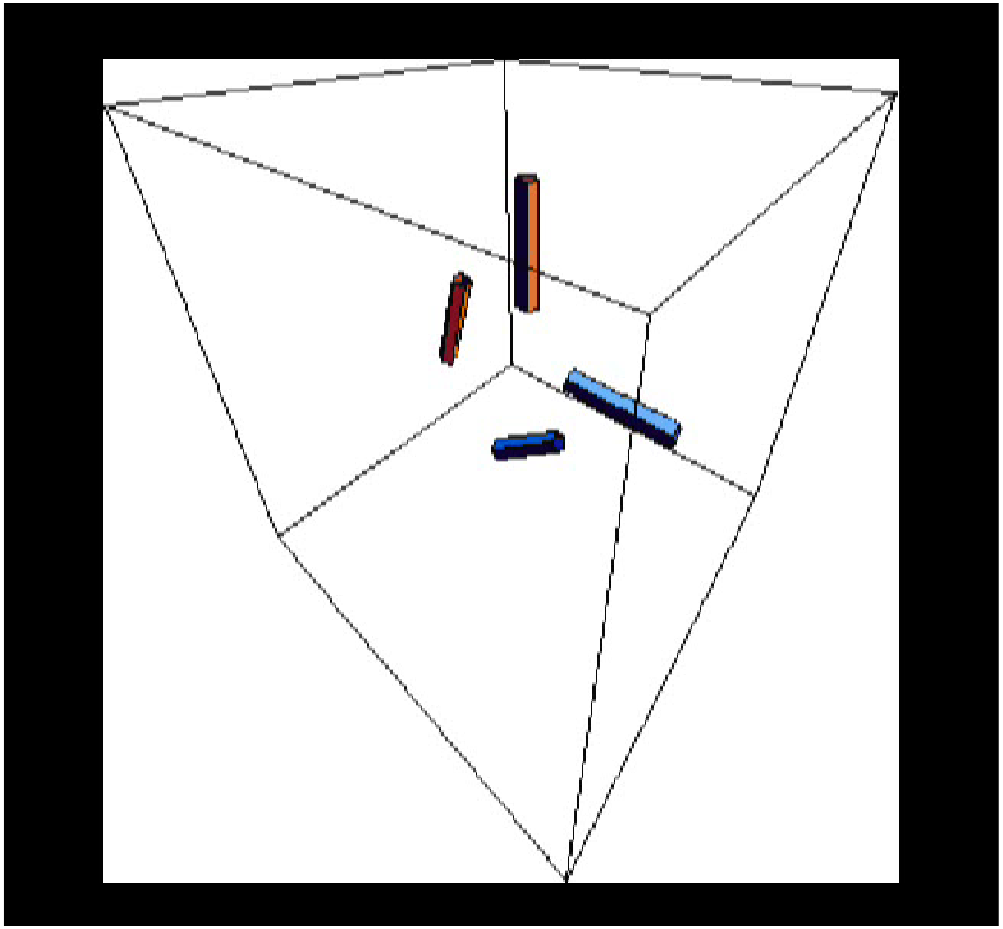


Video: 600 kg s/c, 75m diameter formation, 0.5 rev/hr

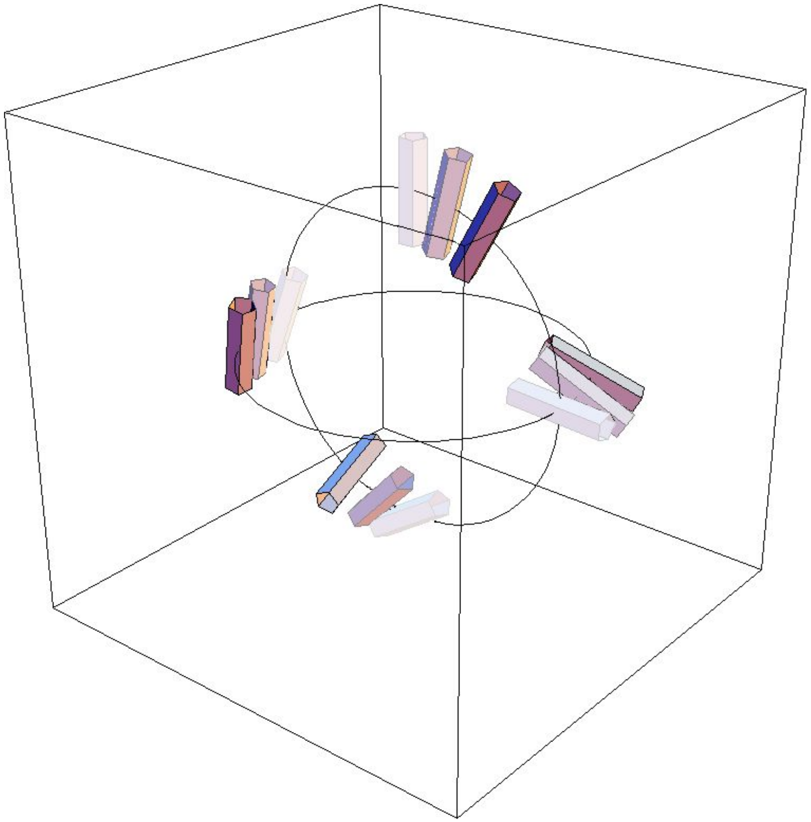


3-D Formations

- We also have the ability to solve for complex 3D motion of satellites.



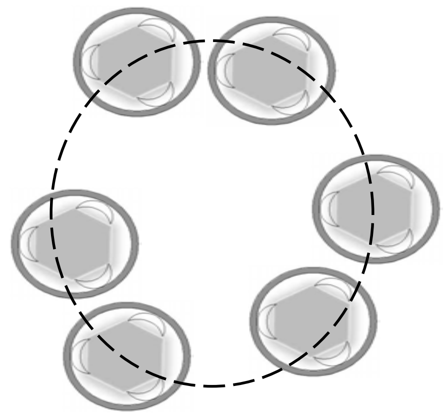
Video: Complex 3-D Motion



EMFF Applications

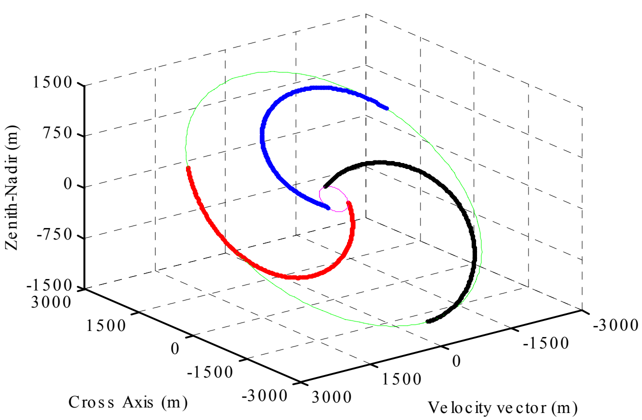
Sparse Apertures

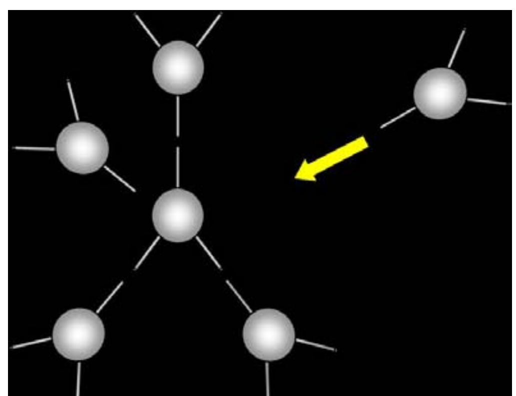
Distributed Optics



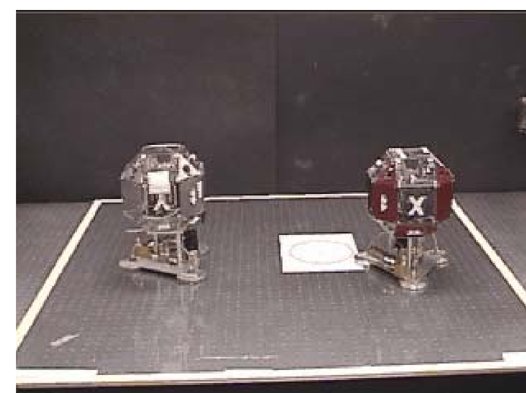
EMFF Secondary Mirrors

Cluster Reconfiguration

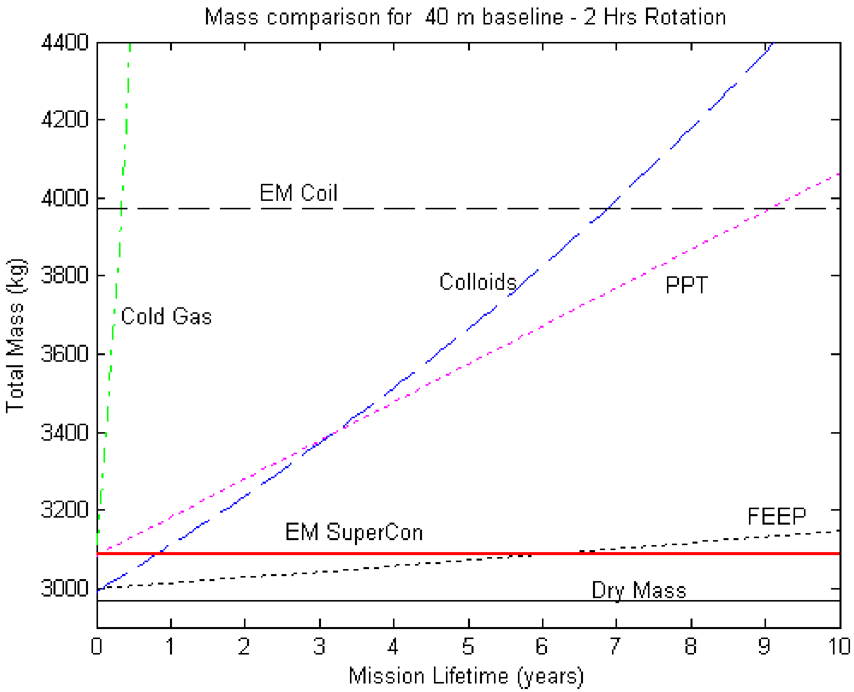


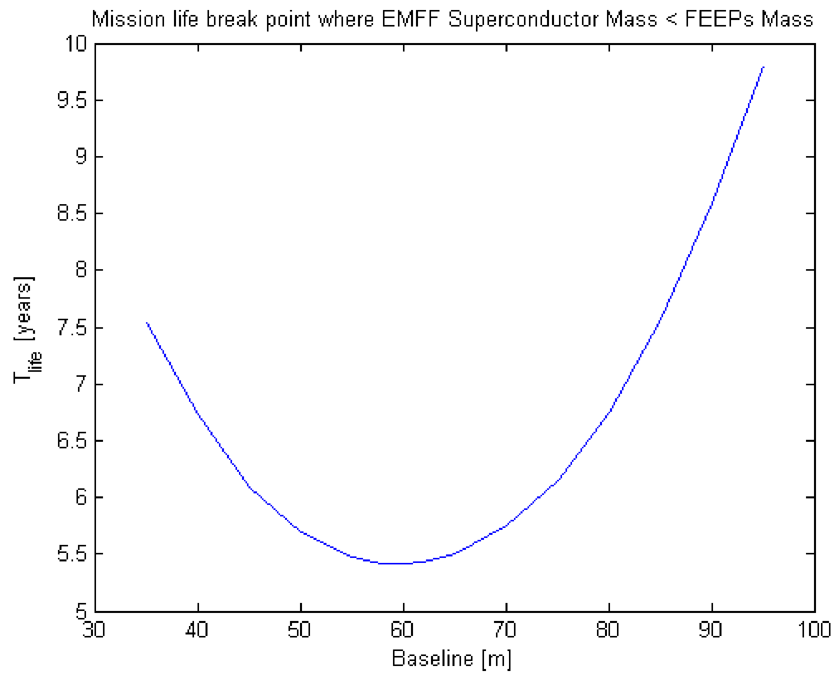


Docking



TPF Case Study

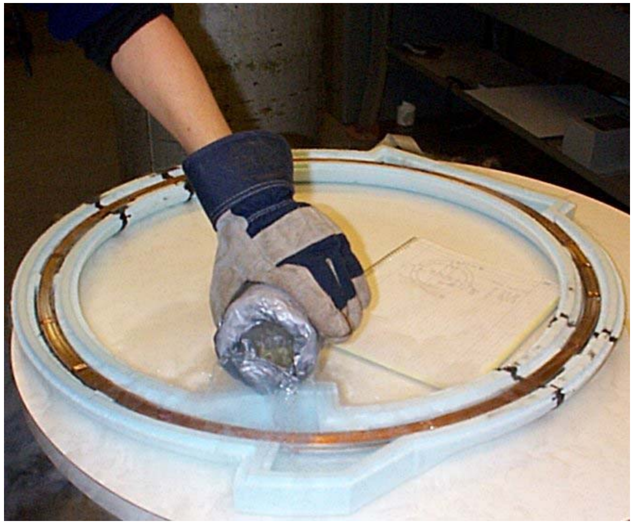




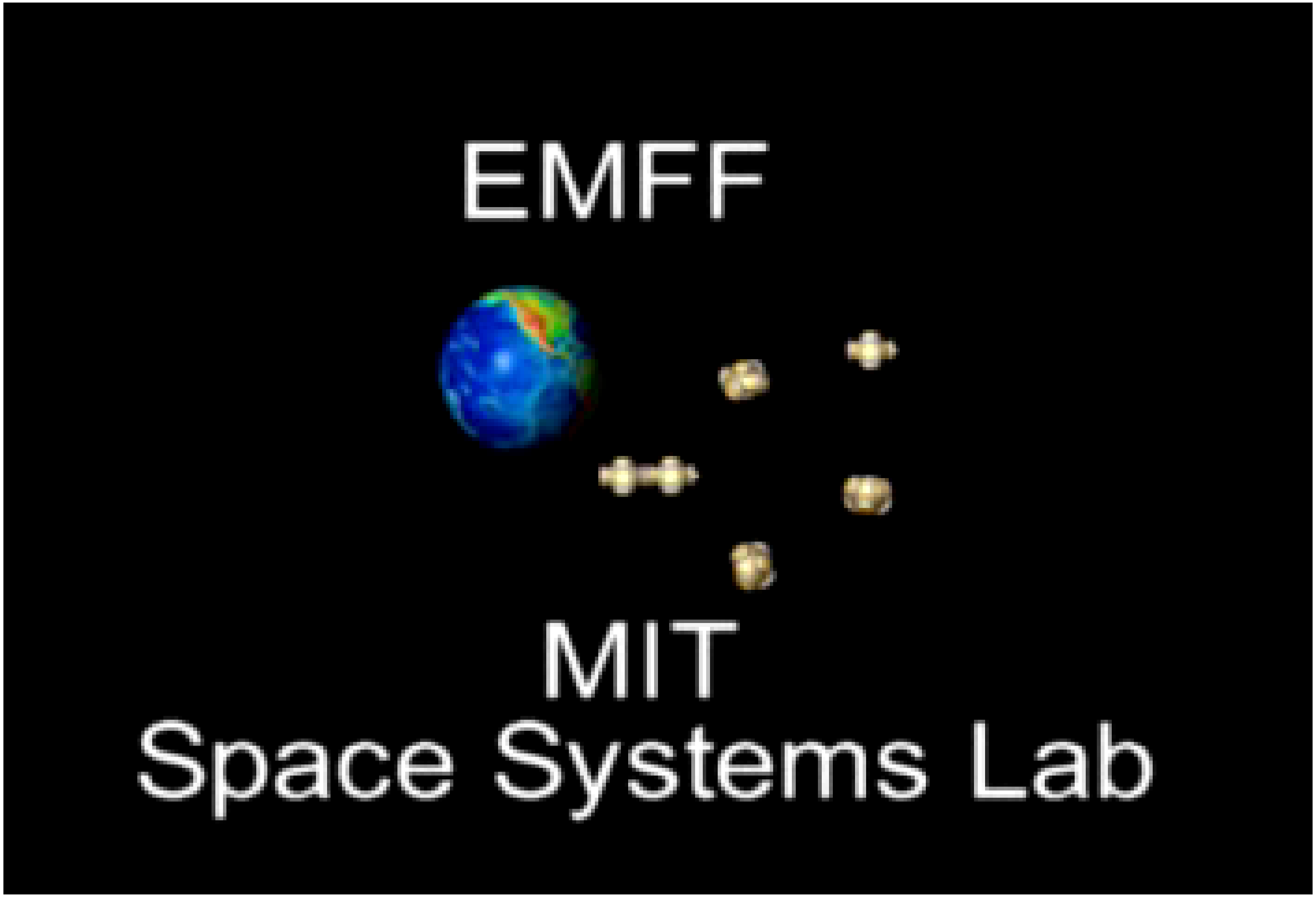
- ***Cold Gas -*** Low I_{sp}, high propellant requirements
  - Not viable option
- ***PPTs and Colloids -*** Higher I_{sp}
  - still significant propellant over mission lifetime
- ***FEEPs –*** Best for 5 yr mission lifetime
  - Must consider contamination issue
  - Only 15 kg mass savings over EMFF @ 5 yr mark
- ***EM coil*** (R = 4 m) (M_{tot} = 3971 kg)
  - Less ideal option when compared to FEEPs even for long mission lifetime
- ***EM Super Conducting Coil*** (R = 2 m) (M_{tot} = 3050 kg)
  - Best mass option for missions > 6.8 years
  - No additional mass to increase mission lifetime
  - Additional mass may be necessary for CG offset
    - Estimated as ~80 kg

EMFForce Testbed Overview

- 2-D testbed traceable to 3-D
- Exercise all controllable degrees of freedom
- High temperature superconducting wire (HTS)
  - Operates at 9kAmps/cm^2 (Capable of 13kAmps/cm^2)
  - HTS demonstrations at 6MAmps/cm^2
  - 100 wraps, Outer diameter ~0.8 m, Operates at 77K
- Four D-cells drive 70 Amps for 40 minutes



Video: Validation of Degrees of Freedom



Note: to hear audio narration, turn on your computer's sound.

Conclusions

- Many types of missions can benefit from propellantless relative control between satellites
  - Provides longer lifetime (even for aggressive maneuvers)
  - Reduces contamination and degradation

- Optimal system sizing has been determined for relatively small satellite arrays. Currently larger formations are being investigated

- Preliminary validation with the MIT Testbed has been achieved, and more complex maneuver profiles will be accomplished with future upgrades